SUPERCONDUCTING TES BOLOMETERS ABOVE 1K

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ABSTRACT

The discovery of High T_c superconductivity led to the exploration of current-biased superconducting bolometers cooled with liquid nitrogen and optimized to view 300K backgrounds at wavelengths beyond 10 μm.   If such detectors reach the thermal fluctuation noise limit they would be a great improvement over room temperature pyroelectric detectors and thermopiles for many applications. The superconducting detectors fabricated in the 1990's had a number of operational problems, and were typically slow because of the large heat capacity of the materials used .However, voltage-biased (TES) superconducting bolometers operated at low temperatures now show superior operating characteristics and enhanced response speed due to electrothermal feedback. This approach may help higher temperature thermal detectors reach their theoretical potential. We have built and tested a Nb-based TES bolometer cooled with liquid helium at 4.2k. This device is optimized for the background power appropriate for far-infrared spectroscopy at frequencies below 100 cm^{-1} with a commercial rapid-scan Fourier transform spectrometer. The sensitivity of our TES detector is a factor ~ 10 better than that of a semiconducting bolometer optimized for the same operating temperature, linearity and speed of response.

Long wavelength infrared detectors are required for planetary missions which can achieve photon noise limited values of D* when viewing background temperatures of a few hundred K in photometric bandwidths.   Since the power, weight, and complexity required to cool infrared detectors increases rapidly with decreasing temperature, there is a need for moderately cooled long wavelength detectors for such missions. Detector arrays with good operating characteristics would significantly improve imaging and spectroscopy, especially of the cooler outer planets.

Infrared photon detectors for wavelengths λ<10μm, such as photovoltaic and QWIP devices, function well when cooled to 77K. They are widely used for diffraction limited imaging of sources with T~300K. They typically produce values of D* close to the photon noise limit. Narrower band gaps are required for longer wavelengths. Thermal excitations at 77K then cause significant dark current and seriously degrade the performance of photon detectors. The extrinsic long wavelength photoconductors such as Si:As, Si:Sb, Ge:Ga and stressed Ge:Ga, which are used out to 200μm can be photon noise limited on much cooler sources, but require much lower operating temperatures. The far infrared detectors on SIRTF, for example, are operated from 1.5<T<20K.

Bolometric detectors are used for astrophysical applications at longer wavelengths. They are typically cooled to temperatures of 0.3, or even 0.1K Detectors such as room temperature pyroelectric detectors with $D^* \sim 3 \times 10^8$ cm Hz$^{1/2}$ W^{-1} and thermopiles cooled to 170 K with $D^* \sim 3 \times 10^9$ cm Hz$^{1/2}$ W^{-1} are widely used for λ>25μm . These values of D^* are far below the values required for photon noise limited detection of 300K sources.

The discovery of high Tc superconductivity in YBCO with T_C=90K, caused considerable excitement in the infrared detector community. Early reports of a novel photon detection mechanism sensitive at 77K proved illusory. There were many studies of a relatively insensitive response with a time constant of a few ns which was excited by pulsed lasers. This was later shown to be the time constant for the thermal response

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of the YBCO film relative to the substrate[1]. The Berkeley group has actively developed superconducting bolometers for many years. This paper summarizes many of these developments. Conventional current-biased superconducting transition edge bolometers with a heat sink temperature of 77K were proposed by the author[2] and have been built by several groups. A review article by the author describes some of this early work[3].

High film quality proved necessary for the narrow superconducting transitions that gave high responsivity, and especially for low noise. Since heat capacities of most materials at 90K are a substantial fraction of their full high-temperature limit, it is necessary to minimize the thickness of the YBCO film and of the substrate. However, most of the substrates on which high quality superconducting films can be grown are too fragile for thin bolometer substrates. It is difficult to produce high quality films on membranes of Si or low stress silicon oxy-nitride (LSN). Sapphire was frequently chosen as a compromise between strength and film quality. It has the advantage of good thermal conductivity at 90K.

Conventional composite bolometers were made using this technology, which gave significantly lower NEP in the far infrared than a 300K pyroelectric detector, but which had significant operational problems [4,5]. Detectors with thermal conductance G optimized for viewing 300K, had long thermal time constants τ of 100 ms or more because of their high heat capacity. It proved difficult to increase the value of G without adding more heat capacity. The roll-off frequency was close to, or even below the knee of the 1/f noise spectrum. The relatively low impedances of a few hundred Ohms meant that amplified voltage noise was a problem. Antenna-coupled microbolometers were fabricated and tested.[6,7] The thermal spreading resistance into the substrate from the small YBCO provided a time constant $\tau \sim 10^{-3}$s.

These YBCO bolometers suffer from the weaknesses common to all current-biased superconducting transition edge bolometers. Because the resistance rises rapidly with T at the operating point on the transition, the power dissipated by the bias $P_B = I_B^2 R$ also increases with T. This is a positive electro-thermal feedback, which further increases the temperature. To keep the bolometer stable, the bias current I_B must be small enough that the effective loop gain of the feedback is less than unity. This requirement limits the detector responsivity and increases the combination of Johnson noise and amplifier noise to the NEP. Both the low T_C and high T_C versions of this detector require very precise regulations of the bath temperature and have a narrow dynamic range because their operating point (and thus the responsivity) are very sensitive to the level of incident background power. These fundamental features are largely responsible for the fact that current-biased superconducting transition edge bolometers have been rarely used since their introduction in 1942.

In 1995, K. Irwin pointed out that the sensitivity of current-biased TES calorimeters for detection of dark matter (or x-ray photons) could be improved if they were biased with a constant voltage. The electrothermal feedback is then negative. It keeps the sum of the infrared power P_{IR} plus the bias power $P_B = V_B^2/R$ fixed so that the operating point is stable. This idea was quickly applied to infrared bolometers. The review article on bolometers by the author[3] suffers from the defect that it did not anticipate the importance of voltage-biased devices with large (negative) electrothermal feedback. In hindsight, it is possible to feel foolish. The article did contain the words "in principle, thermal runaway in a superconducting bolometer can be avoided by using a constant voltage bias and measuring the bolometer current." There was also a discussion of SQUID readouts!

Electrothermal feedback in a bolometer can be described by the analogy to an operational amplifier with voltage gain A in parallel with a feedback link with voltage gain B. The loop gain ℓ of such a circuit is AB. The circuit gain, which describes the ratio of output to input is $(1+AB)^{-1}$. The current responsivity of a voltage biased TES bolometer, calculated using conservation of energy, can be written $S_I = -\ell/V_B (1+ \ell + i\omega\tau_0)$, where the bare time constant $\tau_0 = C/G$ for a single node model of the bolometer. The quantity that plays the role of a loop gain is $\ell = P_B \alpha/GT$, where $\alpha = TdR/RdT$ is a dimensionless measure of the steepness of the R(T) curve at the bias point on the transition. The largest values of α and ℓ obtainable with a given film can be estimated as follows: If the R(T) curve is fitted to a straight line at its steepest point and the intercepts of this line at R=0 and $R=R_N$ are separated by ΔT, then the maximum value of α is $\sim T_C/\Delta T$. Since about half of the temperature rise T_C-T_S of a voltage biased TES is due to the bias, $P_B \sim G(T_C-$

$T_S)/2$, then $\ell = G(T_C-T_S)/2\Delta T$. For a low T_C superconductor with a sharp transition, ℓ can vary from a few hundred to a few thousand. Smaller values are typical of high T_C films.

In the large gain limit, $\ell >> 1$, the current responsivity given by $S_I = -1/V_B$ is independent of changes in the infrared power loading and the heat sink temperature T_S. This responsivity rolls off when $\omega\tau_0 > \ell$, so the single node time constant τ_0 is reduced by the loop gain giving an effective $\tau = \tau_0/\ell = C/\ell G$. However, the thermal feedback does not reduce the delay in the conduction of heat from the radiation absorber to the thermistor (called the internal thermal time constant). The voltage biased TES is fast, linear, and the responsivity is stable in the presence of changes in T_S or P_{IR}. The output of this detector is the current required to keep $P_B + P_{IR}$ fixed. It is read out with a SQUID ammeter which operates at the bolometer temperature, dissipates very little power, and has large noise margin. With collaborators at Stanford and NIST, the Berkeley Group reported the performance of the first voltage-biased TES bolometer, [8] which was a hot electron device with $T_C \sim 100$mK, published the theory of TES bolometers,[9] pointed out the possible usefulness of high T_C TES bolometers,[10] made detailed comparisons between theory and the performance of a test device,[9] fabricated and tested fully lithographed spider-web TES bolometers on LSN membranes ,[11] designed and tested mesh absorber-coupled TES bolometers suitable for close packed arrays and fabricated 1024 element closed packed array structures ,[12] gave a distributed thermal circuit explanation of apparent excess noise in suspended TES bolometers ,[13] and are working on dual-polarization antenna-coupled TES bolometers with strip-line band pass filters. Their early papers used the descriptive term VSB for the voltage-biased superconducting transition edge bolometer rather than the currently more popular term TES, which is ambiguous about both the bias mode and even the kind of device.

Application of TES bolometer to large arrays depends on the development of output multiplexers which allow a row of bolometers to be read out through a single SQUID ammeter. The NIST group [14] has developed a time-domain multiplexer which uses a SQUID switch at each detector to sequentially switch the outputs of the detectors to the ammeter. The Berkeley group [15] is working on a frequency-domain multiplexer which biases each detector in the row with a different frequency, adds the signals and amplifies them with a single SQUID ammeter. The signals are then separated with ambient temperature lock-in demodulators. One or both of these output multiplexers must work well for the TES technology to live up to its potential.

The Berkeley group has been funded by the NSF to build a 300 pixel array of horn-coupled TES bolometers for the new 12m APEX telescope in Chile and a 1000 pixel array of multiplexed horn-coupled bolometers for the new 7m South Pole Telescope. Both arrays will make unbiased searches for thousands of clusters of galaxies at 150GHz using the Sunyaev-Zeldovich effect. Once clusters are found and redshifts determined optically, the data will be used to deduce the expansion history of the universe and thus place limits on the equation of state of dark energy.

The Berkeley group is also developing an experiment called Polar Bear to measure the polarization anisotropy of the Cosmic Microwave Background using a dedicated ~ 2.5m telescope. The Polar Bear focal plane will be developed in two stages, but will ultimately have ~ 900 pixels consisting of dual-polarization antenna-coupled TES bolometers with integrated strip-line band-pass filters. Other groups are also developing powerful receivers. The most spectacular is the SCUBA-II receiver with two 5,000 pixel arrays of close-packed multiplexed bolometers being developed by NIST and collaborators [14].

The highest temperature voltage-biased TES bolometer made to date has a heat sink temperature $T_S = 4.2$K. It was developed by the Berkeley group for Fourier transform spectroscopy in the far infrared.[16] Both the linearity and the speed of the TES device are important for this application. This bolometer is based on a Nb transition edge sensor with $T_C = 8.1$K. It will operate for absorbed infrared power up to 3×10^{-6} W and has an absorber area of 7 mm^2. The response is inherently linear and the noise equivalent power, NEP = 1.2×10^{-13}W Hz$^{-1/2}$ is dominated by thermal fluctuation noise. This NEP is at least a factor 10 better than that expected for a conventional 4.2K semiconductor bolometer which is optimized for far infrared Fourier Transform Spectroscopy in the far infrared with 1% saturation at the same infrared power. The optical response time $\tau = 1.2$ ms is dominated by the internal thermalization time. A smaller version of this

bolometer could be useful for diffraction-limited spectroscopy of small samples throughout the infrared, or even mid-infrared imaging. Estimates suggest that values of detectivity $D^* > 10^{11}$ cm in $Hz^{-1/2}$ W^{-1} and time constants approaching 270 µs could be achieved.

The successful experience with low T_C voltage biased TES devices suggests that the time has come to seriously investigate high T_C voltage biased TES bolometers. The most promising superconductors for high quality films appears to be MgB_2 with $T_C = 40K$ and YBCO with $T_C = 90K$. The MgB_2 bolometer would be most sensitive with $T_S = 20K$ and the YBCO bolometer with $T_S = 45K$, though somewhat higher values of T_S would still be useful. The film quality must be high for large ℓ and low 1/f noise. The bolometer architecture should be designed to minimize the time delay in the transfer of heat from the absorber to the thermistor (internal time constant) for maximum speed. Feedback should be effective in reducing the external time constant

High T_C SQUID's exist with good enough performance to read out a high T_C TES bolometer. They are less available than low T_C SQUIDs and significant effort may be required to implement them. This is certainly true for a possible high T_C SQUID multiplexer. Such a development should not be undertaken until it is very clear that the properties of a high T_C voltage biased TES bolometers are favorable for important applications. Initially, the performance of the bolometers can be tested with a commercial Nb SQUID operated at 4.2K. One approach is to use planar lithographed flux transformer with a high T_C primary at temperature T_S separated by a small gap from a planar lithographed Nb secondary at 4.2K connected to the SQUID input. Since zero resistance is not required in these circuits, they need not be monolithic high T_C superconducting films.

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